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Derived from an early National Bureau of Standards (NBS) tropospheric trans-horizon propagation data base [1], a particular loss term defined as path attenuation was used in the radar equation to estimate the behavior of signal-to-noise ratio with frequency (10 to 1000 MHz) and distance (50 to 1000 km) including median and 1, 10, 90, 99 percent variability. This loss term depends on frequency, distance, climate, refractivity and an empirically derived attenuation function which takes into account effects of antenna heights. Equivalent antenna temperatures are assumed to be due to galactic noise. Receiver noise is characterized by noise figure. For conveniently chosen system parameters (1 MW transmitter power, 1 Hz receiver bandwidth, antenna gains $G_t = G_r = 1000$), signal-to-noise ratio behavior is illustrated for several target cross sections (e.g. resonant dipole, conducting sphere) as a function of frequency, distance, variability for particular climates. Conversion to other system parameter values is straightforward. The complete details are available from the author [2].

Propagation Study for a Tropospheric Transhorizon Radar

KURT TOMAN, SENIOR MEMBER, IEEE

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The author is with the Propagation Branch, Electromagnetic Sciences Division, Hanscom AFB, MA 01731.

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Optimization of Radio Communication in Media with Three Layers

GERVÁSIO P. S. CAVALCANTE AND ATTÍLIO J. GIAROLA, SENIOR MEMBER, IEEE

Abstract—The electromagnetic radiation of an electric dipole in a medium with three layers is examined using dyadic Green's functions. The far zone field for problems of this nature is primarily determined from the lateral wave. It is shown that the excitation of this wave may be reinforced through a dipole inclination and an optimum position may be determined. The radio losses for typical forests were calculated for vertical and horizontal dipoles and for dipoles with an optimum inclination. The theoretical results are in good agreement with the available experimental data.

I. INTRODUCTION

The analysis of the electromagnetic wave propagation in layered media has been considered by many authors [1]-[7]. A model commonly used to analyze the radio propagation in forests consists of a homogeneous and isotropic dielectric layer placed over a conducting flat earth [8]-[10]. In this analysis the Hertz potential theory is used, and particular attention is devoted to the behavior of the lateral wave.

The use of the dyadic Green's functions for the analysis of the electromagnetic wave propagation in semi-infinite media was described by Tai [11] and a generalization of these functions for the case of an N-layered medium has been recently obtained [12].

In this communication the dyadic Green's functions for a three-layered medium are determined. From these functions the electric fields of the electromagnetic waves radiated from the vertical and horizontal electric dipoles were obtained. In addition, the electric field of the electromagnetic wave radiated from an inclined electric dipole was obtained, and an analysis was developed to evaluate the inclination angle for optimum excitation of the lateral wave. The results are expressed in terms of radio losses between transmitter and receiver and for typical forests.

II. OUTLINE OF THE GENERAL THEORY

The geometry that will be considered here is shown in Fig. 1. An electric dipole with an inclination α with respect to the boundary plane between layers and an observation point are both located in the intermediate layer (medium 2). The height of this layer measured along the z-direction is H, while the height of the other two adjacent layers is infinite.

The source that feeds the electric dipole has a harmonic time dependence given by exp $(-j\omega t)$. The dielectric permittivities of the three media are expressed in their complex form, $\epsilon_n = \epsilon_{rn}\epsilon_0 = \epsilon_n' + j\epsilon_n'' = \epsilon_n'(1 + j\sigma_n/\omega\epsilon_n')$, where ϵ_{rn} is the complex dielectric constant and σ_n is the conductivity of medium $n (n = 1, 2, \text{or } 3)$, ϵ_0 is the free-space permittivity. The real and imaginary parts of the dielectric permittivity of medium n are given by ϵ_n' and ϵ_n'', respectively, and the wavenumber is given by $k_n = \omega\sqrt{\mu_0\epsilon_n}$. The magnetic permeability of any one of the three media is assumed to be equal to the free-space permeability μ_0.

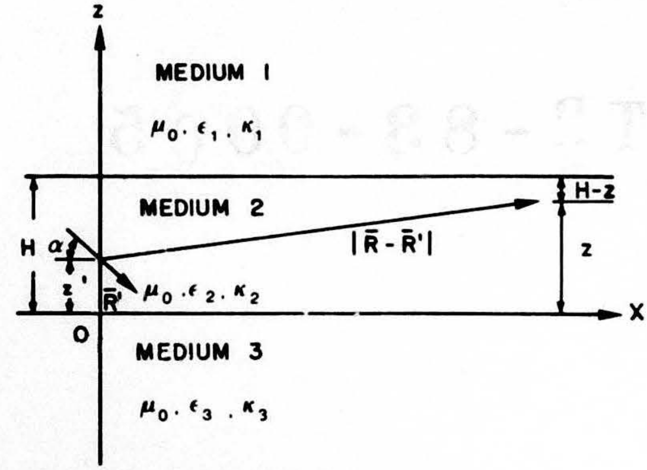

Fig. 1. Geometry for model with three-layered medium.

The wave equation for the electric field E_s in layer s due to a source in layer $f (s, f = 1, 2, \text{or } 3)$ is given by (see Fig. 1):

$$\nabla x \nabla x \bar{E}_s - k_s^2 \bar{E}_s = j\omega\mu_0 \bar{J}_f \delta_s^f, \tag{1}$$

where δ_s^f is the Kroneker delta (δ_s^f equal to one for $f = s$ and equal to zero for $f \neq s$) and $\bar{J}_f$ is the current density from the source.

The electric field at a position $\bar{R}$ from a source at $\bar{R}'$ may be obtained from a dyadic Green's function of the electric type, $\bar{\bar{G}}_e^{(sf)}(\bar{R}/\bar{R}')$, that satisfies the following wave equation:

$$\nabla x \nabla x \bar{\bar{G}}_e^{(sf)}(\bar{R}/\bar{R}') - k^2 \bar{\bar{G}}_e^{(sf)}(\bar{R}/\bar{R}') = \bar{\bar{I}}\delta(\bar{R} - \bar{R}')\delta_s^f, \tag{2}$$

where $\bar{\bar{I}}\delta(\bar{R} - \bar{R}')$ is the unit delta dyadic function and the superscripts (sf) refer to the layer where the observation point and the source position are located, respectively.

Knowing $\bar{\bar{G}}_e^{(sf)}(\bar{R}/\bar{R}')$ and $\bar{J}_f(\bar{R}')$, the electric field may be obtained from (see Tai [11], for example):

$$\bar{E}_s(\bar{R}) = j\omega\mu_0 \iiint_{V_f} \bar{\bar{G}}_e^{(sf)}(\bar{R}/\bar{R}') \cdot \bar{J}_f(\bar{R}')\, dV' \tag{3}$$

where the integral is over the whole volume V_f that contains the source in layer f and $\bar{\bar{G}}_e^{(sf)}(\bar{R}/\bar{R}')$ satisfies the following boundary conditions (for convenience, the functional dependence $(\bar{R}/\bar{R}')$ will be omitted in all dyadic Green's functions):

$$\hat{z} x \bar{\bar{G}}_e^{(sf)} = \hat{z} x \bar{\bar{G}}_e^{(s+1, f)} \tag{4}$$

$$\hat{z} x \nabla x \bar{\bar{G}}_e^{(sf)} = \hat{z} x \nabla x \bar{\bar{G}}_e^{(s+1, f)} \tag{5}$$

at the interfaces $z = 0$ and $z = H$. in addition, $\bar{\bar{G}}_e^{(sf)}$ satisfies the Sommerfeld's radiation condition.

The method of scattering superposition (see Tai [11], for example) is used to obtain $\bar{\bar{G}}_e^{(sf)}$. Thus

$$\bar{\bar{G}}_e^{(sf)} = \bar{\bar{G}}_0 \delta_s^f + \bar{\bar{G}}_s^{(sf)}. \tag{6}$$

The dyadic Green's functions may be expressed in terms of the cylindrical vector wave functions $\bar{M}_{\substack{e\\o}n\lambda}(h)$ and $\bar{N}_{\substack{e\\o}n\lambda}(h)$ (see

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G. P. S. Cavalcante is with the Departamento de Engenharia Elétrica, Universidade Federal do Pará, 66.000 Belém, Pará, Brazil.

A. J. Giarola is with the Departamento de Engenharia Elétrica, Faculdade de Engenharia de Campinas, Universidade Estadual de Campinas, 13.100 Campinas, São Paulo, Brazil.

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Tai [11], for example), where the subscripts e and o indicate even and odd functions, respectively, n, λ, and h are the eigenvalues associated with the ϕ, r, and z coordinates, respectively. The eigenvalues h and λ are related by $h = \sqrt{k^2 - \lambda^2}$.

For simplicity, the subscripts of the vector wave functions $\bar{M}_{\substack{e\\o}n\lambda}(h)$ and $\bar{N}_{\substack{e\\o}n\lambda}(h)$ will be omitted. The prime on these functions $\bar{M}'(h)$, $\bar{N}'(h)$ is used to indicate that they are expressed in terms of the coordinates (r', ϕ', z').

The free-space dyadic Green's function is given by [13]

$$\bar{\bar{G}}_0 = -\frac{1}{k_0^2}\hat{z}\hat{z}\delta(\bar{R}-\bar{R}') + j\frac{1}{4\pi}\int_0^\infty \frac{d\lambda}{h_2\lambda} \cdot \sum_{n=0}^{\infty}(2-\delta_0)\begin{Bmatrix} \bar{M}(h_2)\bar{M}'(-h_2) + \bar{N}(h_2)\bar{N}'(-h_2), & z \geqslant z' \\ \bar{M}(-h_2)\bar{M}'(h_2) + \bar{N}(-h_2)\bar{N}'(h_2), & a \leqslant z' \end{Bmatrix} \tag{7}$$

where δ_0 is the Kroneker delta ($\delta_0 = 1$ for $n = 0$ and $\delta_0 = 0$ for $n \neq 0$). Since the interest of this communication is for fields away from the source region the first term on the right side of (7) is irrelevant and will be omitted from the expressions of the dyadic Green's functions.

The scattering dyadic Green's functions $\bar{\bar{G}}_s^{(sf)}$ are conveniently chosen so that the boundary and radiation conditions for $\bar{\bar{G}}_e^{(sf)}$ are achievable. The result is

$$\bar{\bar{G}}_s^{(12)} = \frac{j}{4\pi}\int_0^\infty \frac{d\lambda}{h_2\lambda}\sum_{n=0}^{\infty}(2-\delta_0)\{\bar{M}(h_1)[e\bar{M}'(-h_2) + e'\bar{M}'(h_2)] + \bar{N}(h_1)[f\bar{N}'(-h_2) + f'\bar{N}'(h_2)]\} \tag{8}$$

$$\bar{\bar{G}}_s^{(22)} = \frac{j}{4\pi}\int_0^\infty \frac{d\lambda}{h_2\lambda}\sum_{n=0}^{\infty}(2-\delta_0)\{\bar{M}(h_2)[a\bar{M}'(-h_2) + a'\bar{M}'(h_2)] + \bar{N}(h_2)[b\bar{N}'(-h_2) + b'\bar{N}'(h_2)] + \bar{M}(-h_2)[c\bar{M}'(-h_2) + a\bar{M}'(h_2)] + \bar{N}(-h_2)[d\bar{N}'(-h_2) + b\bar{N}'(h_2)]\} \tag{9}$$

$$\bar{\bar{G}}_s^{(32)} = \frac{j}{4\pi}\int_0^\infty \frac{d\lambda}{h_2\lambda}\sum_{n=0}^{\infty}(2-\delta_0) \cdot \{\bar{M}(-h_3)[g'\bar{M}'(h_2) + g\bar{M}'(-h_2)] + \bar{N}(-h_3[h'\bar{N}'(-h_2) + h\bar{N}'(h_2)]\} \tag{10}$$

where the coefficients that appear in (8)-(10) are obtained from boundary conditions (4) and (5).

The current density of an electric dipole with an inclination α with respect to the boundary plane between layers, as shown in Fig. 1, may be expressed as

$$\bar{J}_2(\bar{R}') = (p_x\hat{x} + p_z\hat{z})[\delta(x-0)\delta(y-0)\delta(z-z')] \tag{11}$$

where p_x and p_z are the horizontal and vertical dipole moments, respectively.

From (3), (9), and (11) one obtains, for the region $H \geqslant z \geqslant z'$:

$$\begin{aligned}\bar{E}_2(\bar{R}) = -\frac{\omega\mu_0}{4\pi}\int_0^\infty \frac{d\lambda}{h_2}\Bigg[& p_x\Bigg\{[\bar{M}_{o1\lambda}(h_2)(1+a) + c\bar{M}_{o1\lambda}(-h_2)]e^{jh_2z'} + [a'\bar{M}_{o1\lambda}(h_2) \\ & + a\bar{M}_{o1\lambda}(-h_2)]e^{-jh_2z'} + [\bar{N}_{e1\lambda}(h_2)(1+b) + d\bar{N}_{e1\lambda}(-h_2)] \\ & \left(-j\frac{h_2}{k_2}\right)e^{jh_2z'} + [b'\bar{N}_{e1\lambda}(h_2) + b\bar{N}_{e1\lambda}(-h_2)] \cdot \left(j\frac{h_2}{k_2}\right)e^{-jh_2z'}\Bigg\} + p_z\lambda^3\{\bar{N}_{e0\lambda}(h_2) \\ & \cdot[(1+b)e^{jh_2z'} + b'e^{-jh_2z'}] + \bar{N}_{e0\lambda}(-h_2)[de^{jh_2z'} + be^{-jh_2z'}]\}\Bigg]\end{aligned} \tag{12}$$

where

$$a = \frac{R_1^H R_2^H \exp(j2h_2H)}{D^H} \qquad a' = \frac{R_2^H}{D^H}$$

$$b = \frac{R_1^V R_2^V \exp(j2h_2H)}{D^V}$$

$$b' = \frac{R_2^V}{D^V} \qquad c = \frac{R_1^H \exp(j2h_2H)}{D^H} \qquad d = \frac{R_1^V \exp(j2h_2H)}{D^V} \tag{13}$$

with

$$R_1^H = \frac{h_2 - h_1}{h_2 + h_1} \qquad R_2^H = \frac{h_2 - h_3}{h_2 + h_3} \qquad R_1^V = \frac{k_1^2h_2 - k_2^2h_1}{k_1^2h_2 + k_2^2h_1}$$

$$R_2^V = \frac{k_3^2h_2 - k_2^2h_3}{k_3^2h_2 + k_2^2h_3} \qquad D^{H,V} = 1 - R_1^{H,V}R_2^{H,V}\exp(j2h_2H). \tag{14}$$

Using the expressions for $\bar{M}_{\substack{e\\o}n\lambda}(h)$ and $\bar{N}_{\substack{e\\o}n\lambda}(h)$ (see Tai [11], for example) the z component of (12) may be obtained as

$$E_z = j\frac{\omega\mu_0}{4\pi k_2^2}\int_0^\infty d\lambda\,\lambda^2\frac{1 + R_1^V e^{j2h_2(H-z)}}{1 - R_1^V R_2^V e^{j2h_2H}}e^{jh_2(z-z')} \cdot \left\{\left[p_x\cos\phi J_1(\lambda r) + jp_z\frac{\lambda}{h_2}J_0(\lambda r)\right][1 + R_2^V e^{j2h_2H}]\right\}. \tag{15}$$

III. z-COMPONENT OF THE RADIATED ELECTRIC FIELD

The integrand of (15) has two terms, one proportional to the vertical dipole p_z and the other to the horizontal dipole p_x. Each integral will be evaluated separately. The z-component of the radiated electric field due to the vertical dipole is obtained from

$$E_z = q\int_{-\infty}^{\infty}\phi(\lambda)\frac{\lambda^3}{h_2}H_0^{(1)}(\lambda r)\,d\lambda \tag{16}$$

where

$$q = -\frac{\omega\mu_0 p_z}{8\pi k_2^2} \tag{17}$$

$$\phi(\lambda) = \frac{[e^{-jh_2 z} + R_2^V e^{jh_2 z'}][e^{jh_2 z} + R_1^V e^{jh_2(2H-z)}]}{[1 - R_1^V R_2^V e^{j2h_2 H}]} \tag{18}$$

and the Bessel function $J_0(\lambda r)$ was transformed into a Hankel function $H_0^{(1)}(\lambda r)$ in order to change the limits of integration from zero to infinity to the more convenient limits from minus infinity to infinity.

The integral (16) represents the field in medium 2 and results from the superposition of cylindrical waves thar are successively reflected at the interfaces between media 1 and 2, and media 2 and 3, with reflection coefficients R_1 and R_2, respectively.

Since the interest here is the calculation of the fields in the far zone, the Hankel function which appears in (16) may be replaced by its asymptotic expression. In addition, one over the expression that appears in the denominator of (18) may be expressed in an infinite series form (binomial expansion). This however, does not remove the necessity of considering the branch points, as will be done afterwards. After exchanging the integration and the summation operations and using the transformation $\lambda = k_2 \sin v$, (16) may be written as

$$E_z = \sum_{m=0}^{\infty} q' I_m \tag{19}$$

where

$$I_m = \int_{P_0} (e^{-bz'} + R_2^V e^{bz'})(e^{bz} + R_1^V e^{b(2H-z)}) \cdot (R_1^V R_2^V e^{2bH})^m \cdot \sin^{3/2} v \cdot e^{jk_2 r \sin v}\, dv, \tag{20}$$

$$q' = q k_2^{5/2} \sqrt{\left(\frac{2}{\pi r}\right)} e^{-j\pi/4}, \tag{21}$$

$$b = jk_2 \cos v. \tag{22}$$

The solution of the integral in (19) corresponding to the lateral wave at the interface of media 2 and 3 will be strongly attenuated due to the high conductivity of the medium 3 for the cases that were considered here. The lateral wave at the interface 1 and 2 will be calculated in a way similar to that available in the literature [1] and [3]. Thus the z component of the electric field will be given by

$$E_{zb} = -E_{1z} \frac{n_1}{(1-n_1^2)} [1 + R_2^V(v_1) e^{2bz'}] \cdot \sum_{m=0}^{\infty} [R_2^V(v_1) e^{2bH}]^m \tag{23}$$

where

$$E_{1z} = \frac{\omega\mu_0 p_z}{2\pi k_2 r^2} e^{j(k_1 r - \frac{\pi}{4}) + bS} \tag{24}$$

$$b = jk_2\sqrt{1-n_1^2} \tag{25}$$

$$S = 2H - z - z'. \tag{26}$$

Following similar procedure, the z component of the electric field due to a horizontal polarized source may be obtained. The superposition of both fields leads to the expression of the z component of the electric field due to an inclined electric dipole. The result is

$$E_z^I = -E_1 \sum_{m=0}^{\infty} [R_2^V(v_1) e^{2bH}]^m [1 + m(1 + e^{-2b(H-z)})] \cdot [1 + R_2^V(v_1) e^{2bz'}] \cdot \left[\frac{n_1}{1-n_1^2} \sin\alpha + \frac{\cos\phi\cos\alpha}{\sqrt{1-n_1^2}}\right] \quad (\text{V/m}) \tag{27}$$

where

$$E_1 = E_{1z} \frac{\sqrt{p_z^2 + p_x^2}}{p_z} = E_{1z} \frac{1}{\sin\alpha}. \tag{28}$$

IV. OPTIMUM INCLINATION ANGLE

As one has concluded previously, the most important contribution to the radiated field results from the lateral wave. An important characteristic of this wave is that its excitation is associated with the angle of incidence for total reflection, $v_c = \sin^{-1}(n_1)$. Thus an orientation of the source such that its main lobe is oriented in a direction near the angle v_c should intensify the radiated field. For low-loss media maximum radiation occurs in the plane normal to the axis of the inclined dipole, such that $\alpha_m \cong v_c$. For the case of media with losses α_m will depend on these losses.

From (27) one observes that maximum radiation occurs for $\phi = 0$ and $0 < \alpha < \pi/2$ or for $\phi = \pi$ and $0 > \alpha > (-\pi/2)$. For $\phi = 0$ the depencence of (27) in α may be expressed by

$$f(\alpha) = \left|\frac{\sin\alpha}{n^2-1} + \frac{\cos\alpha}{\sqrt{n^2-1}}\right| \tag{29}$$

where $n = 1/n_1$.

For α real the maximum of $f(\alpha)$ occurs for

$$tg2\alpha_m = \frac{2\,\mathrm{Re}\{\sqrt{n^2-1}\}}{|(n^2-1)|-1}. \tag{30}$$

This result is identical to that obtained by Staiman and Tamir [14] for a half-space geometry since the contribution of the lateral wave in the forest-ground interface was neglected for the practical cases considered here. This problem has also been studied for a medium with three layers [15] with the source located inside the intermediate layer and the observation point in the upper layer.

V. RESULTS

The radio loss L_B from an inclined radiating dipole to a vertical receiving antenna, neglecting the influence of the ground on the radiation resistance of the dipole, is given by

$$L_B = 36.57 + 20\log f + 20\log E_0 - 20\log E_z^I \tag{31}$$

where f is the frequency in MHz, E_0 is the unattenuated field strength in μV/m expected from the transmitting system at one mile, and E_z^I is the calculated value of field strength produced as a result of radiation from the transmitting system used to determine E_0 above.

TABLE I
CHARACTERISTIC PARAMETERS OF TYPICAL FORESTS

HEIGHT OF THE TREES	H(m)	10	20	30
PARAMETERS OF THE VEGETATION	ϵ_2	1.1	1.3	1.3
	σ_2(mS/m)	0.1	0.3	1.0
PARAMETERS OF THE GROUND	ϵ_3	20	50	50
	σ_3 (mS/m)	10	100	100

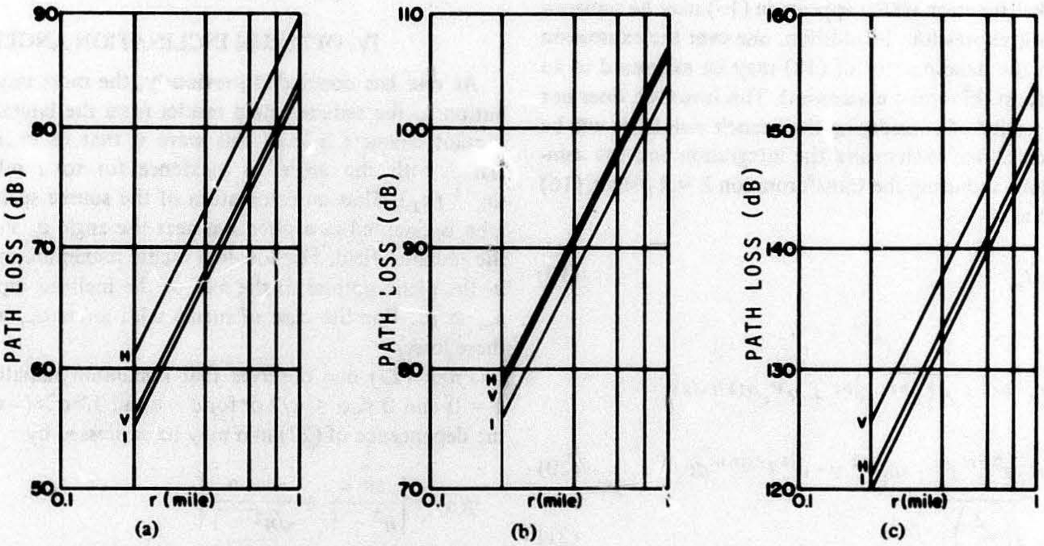

Fig. 2. Predicted path loss for a dipole buried in forest. (a) Tropical "average" forest, $\epsilon_2 = 1.1$, $\sigma_2 = 0.1$ mS/m, $\epsilon_3 = 20$, $\sigma_3 = 10$ mS/m, $\alpha_m = 63.4°$. (b) Tropical "dense" forest, $\epsilon_2 = 1.3$, $\sigma_2 = 0.3$ mS/m, $\epsilon_3 = 50$, $\sigma_3 = 100$ mS/m, $\alpha_m = 46°$. (c) Equatorial "dense" forest, $\epsilon_2 = 1.3$, $\sigma_2 = 1$ mS/m, $\epsilon_3 = 50$, $\sigma_3 = 100$ mS/m, $\alpha_m = 25.9°$. $z = z' = 10$ m. Vertical (V), horizontal (H), and inclined (I) polarizations at 6 MHz.

Due to the large range of parameters measured for forests [16]-[18] it is practically impossible to display curves for all possible combination of these parameters. For purposes of illustration three cases were considered and are shown in Table I.

In Table I the first and second columns correspond to medium and dense tropical forests, respectively, while the third column corresponds to values recommended for the Amazon region (equatorial dense forest) based on the measurement of field strength made by Assis [18] in Tabatinga, Amazon.

In Fig. 2 the calculated path losses are shown as functions of the distance between transmitter and receiver for vertical, horizontal, and inclined polarizations and for the three typical forests considered here for transmitting and receiving antennas located at $z = z' = 10$ m. As may be seen in these figures, the basic transmission loss is improved from 0.5 to 3.0 dB by using an optimum inclination of the transmitting dipole.

In Fig. 3 the lateral wave power-radiation patterns for the three typical forests are shown at a frequency of 6 MHz and for vertical, horizontal, and inclined polarizations. The heights of the transmitting and receiving antennas are the same as those used in Fig. 2. The enhancement of the lateral wave and the increase in directivity may be observed in these figures as the polarization reaches its optimum inclination. This suggests that the enhancement of the lateral wave may increase considerably if an antenna with a high gain is directed along α_m.

VI. CONCLUSION

A method using dyadic Green's functions for the solution of the electromagnetic wave propagation in layered media has been developed. This method presents some advantages with respect to the conventional method (the Hertz potential method), such as 1) the dyadic Green's functions outside the source region allow a higher degree of flexibility with respect to the space coordinates and assure a good exponential convergence; 2) the source may contain an arbitrary current distribution and the medium may be isotropic or anisotropic. The electric fields were obtained considering that the media were isotropic and homogeneous and that the optimization of the lateral wave depends only on the properties of the region near the source. The propagation of electromagnetic waves in anisotropic-layered media has not been as

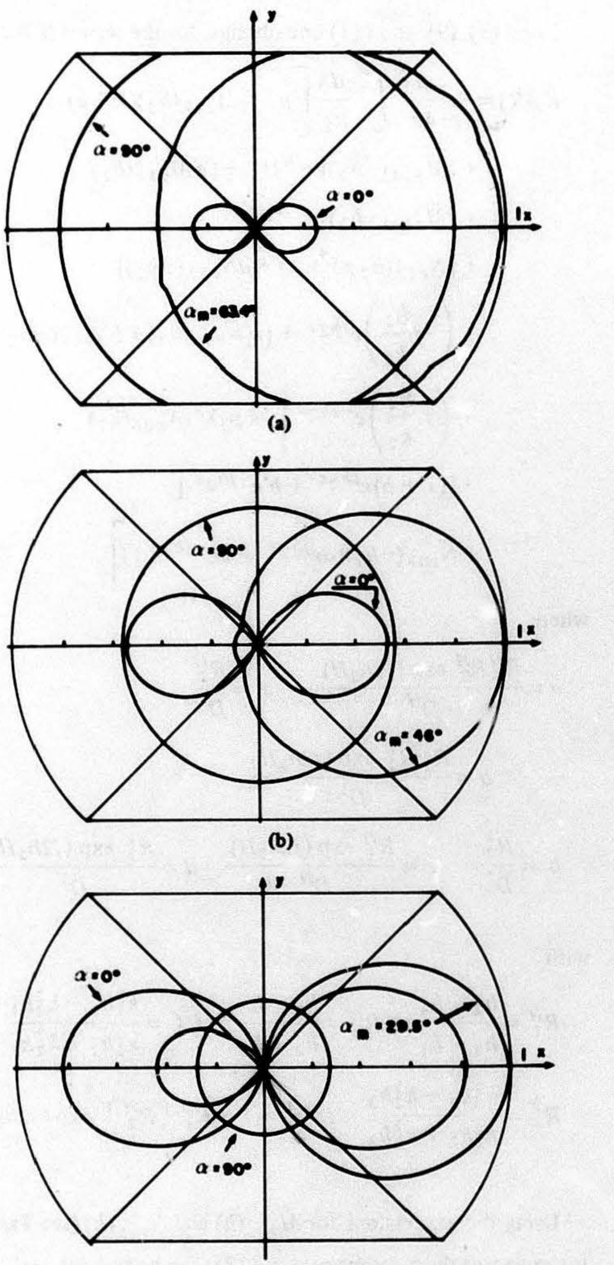

Fig. 3. Lateral wave power-radiation patterns for dipole buried in forest. (a), (b), and (c) are described in Fig. 2. $z = z' = 10$ m. Vertical ($\alpha = 90°$), horizontal ($\alpha = 0°$), and inclined (α_m) polarizations at 6 MHz.

yet widely explored and the use of the dyadic Green's function method may unveil some interesting results.

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